Low Charge Evaporators for Industrial Heat Pumps

Zahid Ayub and Adnan Ayub, Isotherm, USA

Energy usage and its impact on the environment has become an important topic in today's world. One way to handle this issue, on a larger scale, is to use heat pumps for district heating. With the Kigali amendment to the Montreal protocol there are not many options at hand regarding suitable refrigerants. They will be either low GWP nonflammable olefin-based gases or natural refrigerants such as ammonia. The former is expected to be expensive and the latter is toxic. To cope with this challenge, engineers must devise systems that are highly efficient and at the same time carry low refrigerant charge.

Introduction

The heat exchanger business has seen dramatic changes in the last 100 years - shell and tube to micro-fin coils. There have been two distinct businesses that have been prolific users of heat exchangers. Firstly, the oil and gas (OG) industry, and secondly, the refrigeration and air-conditioning (RAC) industry. The OG industry's thrust has mostly been in the area of shell and tube heat exchangers, with very little improvement, whereas the RAC industry has been at the forefront of introducing new technologies, be it shell and tube or plates or coils. There is an obvious reason for this. The OG industry is extremely conservative and tries to shy away from any new technology. On the other hand, the RAC is an extremely competitive industry and tries to strive for better products at lower cost, which can hold lower refrigerant charge, especially after the regulations, such as the Montreal and Kyoto protocols. Low charge issues in particular have become a key factor. Since heat pump business has been gaining importance in the last decade or so, with a driving pitch for higher coefficient of performance (COP), low refrigerant charge, lower global warming impact both direct and indirect, there have been several new developments in the field of heat exchangers, especially the evaporators. This paper will shed some light on this important topic.

Industrial Heat Pump

The basic concept of the use of industrial heat pumps is very simple: use surplus heat from a refrigeration system to heat a community (district), to avoid direct combustion of fuel. The energy used in running the compressor need to be lower than the direct fuel burnt, which also in turn reduces the carbon footprint or carbon impact factor. In order to achieve this, a refrigeration system need to be highly efficient with high COPs. One key player in this puzzle is the evaporator. It is a known fact that for every 1 °C rise in saturation temperature there is close to 2% improvement in the COP of a system. The same applies to the condenser side, but here we will only discuss the evaporator.

Types of evaporators

There are two types of heat exchangers available in the market for use in industrial heat pump applications:

- Shell and Tube
- Plate which are further divided in three sub categories
  - Plate and Frame
  - Shell and Plate
  - Brazed

Each of the above types has its advantages and disadvantages. As mentioned above we will only discuss the latest types that have the features of holding low refrigerant charge and at the same time are high performers, operating with close approach temperatures. Low charge has two main advantages. Firstly, the refrigerant cost, especially for the current high prices of newer low Global Warming Potential (GWP) refrigerants. Secondly, toxicity, for natural refrigerants such as ammonia, which has excellent features such as zero GWP and Ozone Depletion Potential (ODP) but usually is subject to special local regulations and ventilation criteria.

Shell and tube type

Currently there are three types of low-charge shell and tube evaporators that are most suitable for large industrial scale heat pump applications. They are:

Direct expansion: A typical direct expansion (DX) evaporator as shown in Figure 1 has refrigerant in the tubes and the fluid being cooled in the shell. The main advantage of this configuration is the ability to work with low charge

Fig.1: Shell and tube DX evaporator

per kW capacity. The disadvantage is that the fluid being cooled is on the shell side and mechanical cleaning is not possible. The second disadvantage is that because of control related issues they are not available for larger capacities, so for those applications banks of multiple units are required. Oil management could also be an issue, especially in case of immiscible oil/refrigerant combination. Several boiling correlations are available in the open literature such as Shah (1982).

Spray: A spray evaporator also has low charge characteristics and the key mechanical advantage is that the fluid being cooled is in the tubes, so cleaning is possible. The disadvantage is that for better heat transfer a pump is required to spray the refrigerant onto the bundle surface. Improper wetting can result in lack of heat transfer and optimal capacity will not be attained. A typical spray evaporator is shown in Figure 2. Zeng et al. (1995) proposed the following correlations with a non-dimensional heat flux, φ, for a dimensional heat flux, q''. To account for the effect of saturation temperature, a reduced pressure ratio was also added to the correlations as follows (for an explanation of symbols, se list at the end of the article):

$$Nu = 0.0568\ Re^{-0.0058}\ Pr^{0.193}\ p_r^{0.323}\ \varphi^{1.034}$$

$$Nu = h/k\ (\upsilon^2/g)^{1/3}$$

$$Re = 2\Gamma_f/\mu$$

$$\varphi = q''D/(T_{cr} - T_s)k$$

Fig. 2: Shell and tube spray evaporator

Shell side DX: this is the latest innovation and has the combined qualities of both of the above. The refrigerant is direct expanded on the shell side and therefore there is no requirement for a pump, and because the fluid being cooled is in the tubes, cleaning of tubes is possible. Figure 3 shows a typical evaporator of this type. It holds low refrigerant charge, oil management is simple and because no liquid maintenance is required, the control

Fig. 3: Shell and tube "Shell Side" DX evaporator

system is simple too. Ayub et al. (2017) presented the following correlation for ammonia which has been found equally applicable to other refrigerants:

$$\mathbf{h_{tp} = 70\ q''^{0.9-0.4p_r^{0.1}}\ p_r^{0.55}(-\log p_r)^{-0.6}\ e^{-0.075T_{sup}}}$$

In order to further reduce the size of shell and tube evaporators, various enhancement techniques could be applied, such as high nucleate boiling surfaces that are currently available on the market.

Plate type

There are basically three types of plate exchangers that are candidates for heat pump applications. They are:

Semi-welded plate and frame: two adjacent chevron plates are welded to make up a cassette or module. This keeps the refrigerant confined within the welded cavity and eliminating a flow gasket. Figure 4 shows a typical semi-welded plate and frame exchanger. However, it is not a gasket-free unit. There is a slight misconception in the industry regarding welded plates. Many users believe that the plate pairs are 100% welded together. Unfortunately, that is not the case. In order to maintain the refrigerant flow, only O-ring gaskets maintain the seal, i.e., for every single cassette, there are still two O-Ring gaskets. These gaskets are around the ports where the velocity is maximum and hence highly prone to a leak—most of the leaks reported by the operators have been around the ports. Some advantages are compactness and expandability; a negative feature is higher maintenance cost due to potential leakage issues. Recently Ayub et al. (2019) presented a universal correlation for evaporator applications as follows:

$$Re_{eq} = \frac{G_{eq} D_h}{\mu_l}$$

$$Bo_{eq} = \frac{q''}{G_{eq} h_{fg}}$$

$$G_{eq} = G\left[(1 - x_m) + x_m\left(\frac{\rho_l}{\rho_g}\right)^{0.5}\right]$$

$$Nu = \left(7 + 4.5\,{}^{\beta}\!/_{\beta_{\max}}\right) Re_{eq}^{\left(-0.3\frac{\sigma_{Ref}}{\sigma_{ammonia}}+3\right)}\ Bo_{eq}^{-0.2}$$

Shell and Plate: Shell and plate combines the advantages of shell and tube and plate and frame technologies, with high mechanical integrity inherent to shell and tube and the superior thermal characteristics of the plate and frame. A plate pack is welded together in such a way that the shell side is isolated from the plate side, and there is no gasket for sealing purposes except an O-ring for a body flange in the case of a removable plate pack. Figure 5 shows a shell and plate exchanger. One key disadvantage is its vulnerability to weld leakage in case of a weak weld as shown in Figure 6 which shows a normal weld and a weak weld that leaked after a few cycles of operation. The design criteria are the same as plate and frame.

Brazed Plate: Figure 7 shows a typical compact brazed exchanger. Because of size limitations they are not geared for large capacity industrial heat pumps. They are fully brazed and therefore do not require gaskets. Fluid mixing can only occur in case of plate puncture. They cannot be mechanically cleaned and are thus limited to non-fouling applications. Design criteria are the same as plate and frame.

Comparison

A quick comparative analysis was performed for all the above cases as shown in the table below. A typical sea water-based heat pump application was considered for a 1000 kW evaporator capacity with sea water inlet and outlet temperatures of 8 °C and 4 °C, respectively. Ammonia at saturated temperature of 2 °C. Except for the capacity, the terminal temperatures are exactly the same as at the world's largest ammonia heat pump in Drammen, Norway (Ayub, 2016). The material in contact with sea water was titanium.

Type	Charge (kg)	Price ($, 2019)
DX- Tube	65	59,516
Spray	90	82,477
DX- Shell	46	68,732
PHE (with drum)	209	61,460

Conclusion

A brief comparative analysis of various types of heat exchangers used as evaporator in an industrial heat pump application is presented. The two major types of exchangers are shell and tube and plate type. Each type has sub-categories depending on its usage and geometry characteristics. Each type also has pros and cons that need to be considered carefully at the time of selecting the equipment. The key design criterion is the selection of appropriate two-phase boiling coefficient. The paper presents correlations for each type that can be useful for design engineers. In the wake of environmental issues, especially after the Kigali 2016 amendment, the entire refrigeration industry is striving for low charge systems. This paper provides a brief analysis of charge/kW for each heat exchanger type. The latest shell and tube with shell side direct expansion turned out to be the optimal in this category.

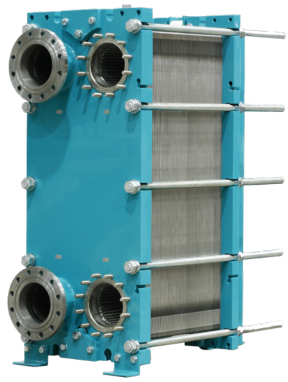

Fig. 4: Semi-welded plate and frame exchanger

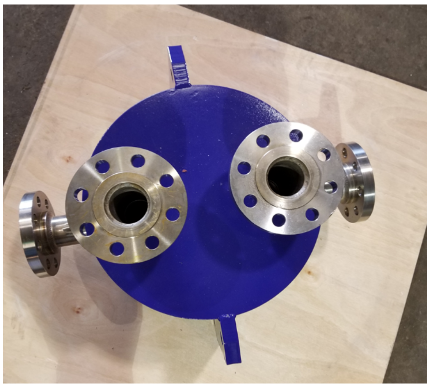

Fig. 5: Shell and plate exchanger

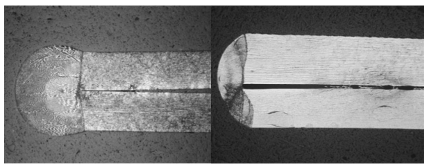

Fig. 6: Normal and failed weld

Fig. 7: Brazed plate exchanger

Nomenclature

Bo	Boiling number
D	Tube outside diameter
G	Mass flux, kg/m^2-s
g	Gravitational acceleration, m/s^2
h	Heat transfer coefficient, W/m^2-K
h_{fg}	Latent heat, kJ/kg
k	Thermal conductivity, W/m-K
Nu	Nusselt number
p_r	Reduced pressure
Pr	Prandtl number
q"	Heat flux, W/m^2
Re	Reynolds number
T	Temperature, K
x	Quality
Γ_f	Liquid flow per unit tube length, kg/m
ρ	Density, kg/m^3
β	Chevron angle, degree
μ	Dynamic viscosity, N-s/m^2
υ	Kinematic viscosity, N/s^2
φ	Non-dimensional heat flux
σ	Surface tension, dynes/cm

Subscript

ammonia	Ammonia as reference refrigerant
cr	Critical
eq	equivalent
g	gas phase
h	hydraulic
l	liquid phase
m	mean
Ref	Working refrigerant
max	maximum chevron angle, degrees
s	Saturation
sup	superheat
tp	two phase

References

[1] Ayub, Zahid H., Tariq S. Khan, Saqib Salam, Kashif Nawaz, Adnan H. Ayub and M. S. Khan, 2019, Literature survey and a universal evaporation correlation for plate type heat exchangers, *International Journal of Refrigeration*, 99, 408-418.

[2] Ayub, Zahid H., Ahmad Abbas, Adnan Ayub, Tariq Saeed and Javed Chattha, 2017, Shell side direct expansion evaporation of ammonia on a plain tube bundle with exit superheat effect, *International Journal of Refrigeration*, 76, 126-135.

[3] Zahid Ayub, 2016, World's Largest Ammonia Heat Pump (14 MWh) for District Heating in Norway – A Case Study, *Journal of Heat Transfer Engineering*, Vol. 37, Nos. 3-4, pp. 382-386.

[4] Shah, M. M. 1982, Chart correlation for saturated boiling heat transfer: Equations and further study, *ASHRAE Transactions* Vol. 88(1): 185-196.

[5] Zeng, X., Chyu, M.-C., and Ayub, Z. H., 1995, Evaporation Heat Transfer Performance of Nozzle-Sprayed Ammonia on a Horizontal Tube, *ASHRAE Transactions*, Vol. 101, pt. 1: 136-149.

[6] Zeng, X., Chyu, M.-C., and Ayub, Z. H., 1995, Nozzle-Sprayed Flow Rate Distribution on Horizontal Tube Bundle, *ASHRAE Transactions*, Vol. 101, pt. 2: 443-353.

ZAHID AYUB
PH.D., P.E.
Isotherm
USA
zahid@iso-therm.com

https://doi.org/10.23697/23e8-3s26